Multispacecraft Electrostatic Tractor with Swarm Optimization

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Abstract

In this paper we propose and analyse a multispacecraft approach to the problem of deflection of a NEO object. The Electrostatic Tractor is a concept where deflection occurs because of a satellite and the asteroid electrically charged interaction. Although the physical laws which describe this phenomenon are well established, a number of practical questions are still being investigated. There are technological uncertainties as well, as it is not clear by now how a satellite can sustain the voltage required for this objective with few fluctuations and interactions with the satellite subsystems. Some authors, like E. Messerchmidt [1] provide some calculations arguing that a bigger spacecraft will be needed with a number of specifications to isolate the other subsystems. Some models have been proposed so far, but none can predict exactly which will be the behaviour of the satellite-asteroid interaction.

Therefore, it is advisable to think in a system formed by a number of satellites, which may co-ordinately contribute to the overall generated power. Given that a number of real-time complex decisions will have to be made in the approach phase to the asteroid as well, we propose a multisatellite solution. The dynamics of the entire multi-body system are simulated and analyzed in order to predict its time of response and adaptability. We propose a distributed control system with an artificial intelligence agent in every satellite, who will be capable of automatically drive the behaviour of every satellite. As the real composition and electrical response of the asteroid is far from being totally predictable, such an approach will have a better margin of success and a fast response to every possible deviation from the models from which the system had been designed.

A number of different swarm intelligence strategies are simulated and analyzed in this paper using state-of-the-art numerical simulators platforms such as Matlab and Simulink. In conclusion, electrostatic tractor is capable of deflecting a NEO like the Apophis asteroid, and the multisatellite concept with distributed artificial intelligence control allows counteracting the uncertainties existing in current models.

INTRODUCTION

A number of different strategies have been proposed to address the problem of changing the orbit of an asteroid. Kinetic impactors are by far the ones more widely investigated. However, when we come across with the problem of a NEO (Near Earth Object) deflection, a 'tractor beam' has the advantage of providing a more smooth and controllable way to modify the object orbit. This approach can be of significant advantage when dealing with such an object like 99942 Apophis. A number of initiatives are under way to measure and predict the exact path of its orbits, so that trajectory uncertainties can be reduced. Historical results from several spacecraft encounters and more than 300 experiments have shown [2] reliable predictive results, suggesting that 1.0 arcsec uncertainties are a good estimation.

The concept of a non-impact tractor to deflect an asteroid was first introduced as a Gravity Tractor by Lu and Love [3], and then Schwickart et al. [4] further applied this concept to the particular case of 99942 Apophis and 2004VD17. Behind this concept we may find the idea of taking into account the mutual gravitational interaction. Such an approach is quite useful for a certain NEO mass, but not the case of a small asteroid as the gravity forces are not strong enough.

It has been recently proposed [5] the possibility of an Electrostatic Tractor in order to overcome these limitations. Such an electrostatic deflector beam will be useful in this specific problem, as electrostatic forces are stronger than gravitational ones in short-term scenarios with small-sized NEOs involved. The authors argue that the maximum force applicable to the asteroid by a given deflection strategy is a measure of its efficiency. Based on this assumption, they provide an estimation of how to provide such a force in the case of the electrostatic concept.

The efficacy of the electrostatic deflection concept relies on the amount of charge that we are able to maintain on both the asteroid and an isolated spacecraft. In this model, the authors assume that the asteroid is a conductive, spherical solid body. Another assumption of this particular model is that of no large volume of charge will be lost to the surrounding space as a result of the electrostatic repulsion between loose particles on the asteroid surface. Calculations are given for a 100m radius asteroid, in order to charge negatively the asteroid at -20kV. Maintaining the charge on the asteroid surface is a costly process in terms of power, with an estimation of 20kW for a 100m radius on an asteroid at 1AU.

Detailed calculations are provided in [5] for the evaluation of the electrostatic force between the asteroid and the spacecraft where a perfectly spherical and conductive asteroid immersed in the space plasma is assumed. However, technical limitations are present when dealing with the problem of examining if an isolated spacecraft is able to really deliver the very high voltage claimed for.

Different concerns have been raised on whether this concept of charging the asteroid can be feasible. Little is known on spacecraft charge control on an asteroid. Models of charge distribution in the surface of the asteroid can be very limited, and also the hypothesis of a conductive body is quite weak, so a complex charge diffusion process is more likely to happen.

Therefore, we can see that uncertainties on the problem of deflecting a NEO like 99942 Apophis with an electrostatic tractor don't arise mainly from the estimation of its trajectory, but from the technological difficulties of providing such high voltages on its surface; and also from weak models of its charge distribution.

We propose a more robust approach which takes into account the limitations behind an isolated spacecraft concept. Instead, a number of small satellites are used. The satellites are self-controlled with a distributed artificial intelligence control system, based on intelligent agents in every satellite. Swarm optimization techniques are simulated in order to study which approach is best to produce the desired charge on the asteroid in the right deflection direction.
The outline in this paper is as follows: First, we evaluate the efficiency of a multispacecraft approach in terms of the dynamics of the system and the electrostatic charge obtained. Second, we analyse some optimization techniques in order to coordinate the multispacecraft system in real-time. Finally, we estimate the number of resources involved and we compare it with the original isolated spacecraft concept.

1. THE MULTISPACECRAFT ELECTROSTATIC TRACTOR

Potentials such as high as 20 kV have been considered for different isolated spacecraft designs. For potentials up to 40 kV the overall charge has been calculated in an isolated spacecraft [5] by means of Child Law [6]. However, some designs should be fully analyzed in order to see if they can really deliver the very high voltages claimed. Different concerns have been raised on whether the charge on the asteroid can be deployed via an alpha emitter, or if the charge distribution mechanisms are fully understood.

A different approach is to deploy the needed charge as a sum of different small satellites contribution. Such contributions will individually be of a lesser value, and therefore a reduced potential level will be needed.

A multispacecraft approach will be able to minimize the single voltage needed to be provided to every single object. Precise evaluation of the electrostatic field obtained on the surface of the asteroid, as a result of different charging techniques and positions estimates that no more than 12% of potential energy is lost as a result of interaction of different charging spacecrafts. Moreover, we are interested in providing a deflection force equivalent to that of an isolated spacecraft. We evaluate the available force in different scenarios from 3 to 15 spacecraft located at distance r from the centre of mass of an asteroid having a surface potential V_0 . By numerical simulation we obtain that 5 100kg spacecrafts charged at 10kV will produce a charge equivalent to that of the isolated spacecraft of 500kg charged to 20kV, assuming that they are immersed in a plasma having the same Debye length of 7.40 mm.

When decreasing the spacecraft mass, and the required potential charge we are easing the limitation constraints of providing such very high power on a medium size spacecraft. Other approaches have been obtained when varying the mass and the number of spacecrafts providing a range of available choices to charge the asteroid.

The robustness of this approached is better than that obtained with a single spacecraft, provided that a distributed coordination system exists. The uncertainties of a single spacecraft deflection model can be reduced if the design includes a fast real-time correcting system. This system is proposed to be a distributed intelligent agent system.

In artificial intelligence, an **intelligent agent (IA)** is defined to be an autonomous entity which monitors and acts upon an environment and directs its activity towards achieving goals, which may involve that it is acting as rational [7]. Intelligent agents are often related to software agents, autonomous software programs that carry out tasks on behalf of users. In our design, Model-based agents will be used as they can handle partially observable environments. Its current state will be stored inside the agent maintaining the part of structure which describes the part of the system that cannot be seen. This behaviour involves that we need at least, partially, the dynamics of what electrostatic field, and thus charge, is obtained at every moment in the charging and deflection process, as well as distance to the object. As this information is independent of the actual physical processes taking place in the asteroid, we could design a charging system independent of the uncertainties of our physical asteroid model. An electrical sensor, optical distance measuring and a software design will only are needed, as well as a transmitting link between the agents of the system. Different optimization techniques will be discussed in the next chapter.

2. SWARM OPTIMIZATION

Among all known techniques of optimizing different intelligence agents, the swarm optimization approach is the one that provides best results when dealing with decentralized, self-organized systems. The so-called **Swarm intelligence** (SI) concept was introduced by Gerard Beni and Jing Wang in 1989, in the context of cellular robotic systems [8].

SI systems are typically made up of a number of simple agents or "boids" interacting locally with one another and with their environment. Those agents follow simple rules, which makes it easy to implement in a small satellite, and although there is no centralized control structure, interactions between such agents lead to the emergence of rational global behaviour, unknown to the individual agents. Natural examples of SI include ant colonies, bird flocking, animal herding, bacterial growth and fish schooling. The application of swarm principles to robots is called swarm robotics, whereas swarm intelligence can also be applied to a set of algorithms which provide rational-like behaviour when implemented on a multi-agent system.

We simulated and analysed the efficiency of three kinds of swarm algorithms to our problem of coordinating a multispacecraft system in order to maintain the same amount of charge on the 100m radius asteroid, and therefore maintaining the desired deflection electrostatic force.

- Ant Colony optimization (ACO)

ACO methods rely on the basis of the actions of an ant colony. These methods are useful in problems that need to find paths and goals. Artificial intelligent agents locate optimal solutions by moving through a parameter space representing all possible solutions. In our case, deviation from deflection trajectory, electrical field and distance to the asteroid and the nearest satellite are taken into account. The single spacecrafts, like ants, will record their positions and the quality of their solutions, so that in later iterations more ants locate better solutions [9]. Some variations exist such as the bees algorithm to this approach.

- Particle swarm optimization (PSO)

PSO is a global optimization algorithm which deals with problems where a solution can be represented as a point or surface in an n-dimensional space. Hypotheses are plotted and seeded with an initial velocity as well as a communication channel between the particles [10]. The main advantage of such approach over other global optimization strategies is that the large numbers of members that make up the particle swarm make the technique impressively resilient to the hazard of having local minima.

- Stochastic diffusion search (SDS)

SDS is an agent based on probabilistic global search and optimization technique best suited to problems where the objective function can be decomposed into multiple independent partial-functions. Each agent maintains a hypothesis which is iteratively tested by evaluating a randomly selected partial objective function parameterised by the agent's current hypothesis. A positive feedback mechanism ensures that, over time, a population of agents stabilise around the global-best solution.

We extensively applied the three approaches to the system a multispacecraft of n satellites, with n ranging from 3 to 15, while allowing the asteroid to randomly deviate from its position, and from its desired electrostatic charge, assuming that a near-instant communication is allowed between two consecutive agents, each agent implemented in a determined spacecraft. Simulations were performed with Matlab-based routines on a state-of-the-art computer machine, allowing the simulations to be repeated up to 1.000 times for every deflection in order to take into account different random deflection scenarios.

It was found that by far, the more efficient way to control the multispacecraft behaviour was the PSO algorithm. It was allowed in this case, to take into account previous deviations from the original distance between the agent and the charging asteroid. The optimization was enhanced when increasing the number of agents involved.

Significant statistical differences were found ($p<001$) when comparing the PSO algorithm, with the other two approaches, with random scenarios with the same number of spacecrafts involved. Although ant optimization different variations, and stochastic diffusion search, showed also convergence to a single deflection path maintaining the charge on the asteroid, the PSO compensated quickly the overall result, providing a hint on what optimization technique to use in this particular application we are dealing with.

3. EFFICIENCY AND AVAILABLE RESOURCES

A precise estimation of the cost of a multispacecraft electrostatic tractor will depend on a number of factors such as number of satellites involved, mass reduction in comparison with a single, isolated spacecraft tractor; electrostatic potential required for every spacecraft, and complexity of the intelligent agents implemented in every case.

A rough analysis of the overall cost of the mission will certainly be based on the maximum mass per satellite to be lifted to Near Earth Orbit, and the number of satellites involved. If we reduced, as we discussed in the first part of the paper, the maximum mass to no more than 100kg then the total cost of the multispacecraft mission can be significantly reduced. We have seen that the optimization techniques work better when increasing the number of satellites, so a balance between better real-time efficiency and cost should be decided. In any case, it has been seen that this type of approach provides a global reliability that does not depend on the lack of accuracy of our physical models that may explain who charging occurs on the deflected asteroid.

We may suggest that an increase up to 5 to 7 satellites while reducing the electrostatic potential for every single satellite in the system will strongly increase the reliability of the mission, with an increase in total cost that can be assumed, as the risk of failure will diminish.

CONCLUSIONS

We have analyzed the concept of a multispacecraft electrostatic tractor with swarm optimization. Such an approach is useful to control small-sized asteroids in real time, and in particular the case of the 99942 Apophis. A multispacecraft approach has found to be more feasible in terms of maintaining a -20kV charge on the asteroid. However, a very fast coordination between the satellites is needed in order to keep up the electrostatic field required. Intelligent agents on board of every spacecraft have been found to be a distributed control system of providing such kind of coordination without the need of a central Earth coordination site, avoiding propagation delays. A number of swarm optimization strategies have been evaluated, with better coordination in terms of a rapid response to the dynamics of the asteroid-multispacecraft system. Particle swarm optimization algorithms were found to be significantly better when responding to random deviations to the desired deflection trajectory. The number of available resources is a limitation to this approach, but a good balance between total cost and effectivity has been found to be between 4 and 6 satellites providing a force corresponding to a maximum charge of -10 kV.

Such an approach will have the advantage of providing a more robust solution to the problem of deflecting a small-sized asteroid, given the technological current limitations of an isolated electrostatic tractor.

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